AN INTRODUCTION TO LAUNCH VEHICLE GUIDANCE ALGORITHMS

PRESENTED TO

M.TECH (GNC)

DEPT OF ELECTRICAL ENGINEERING

COLLEGE OF ENGINEERING

THIRUVANANTHAPURAM

PRESENTED BY

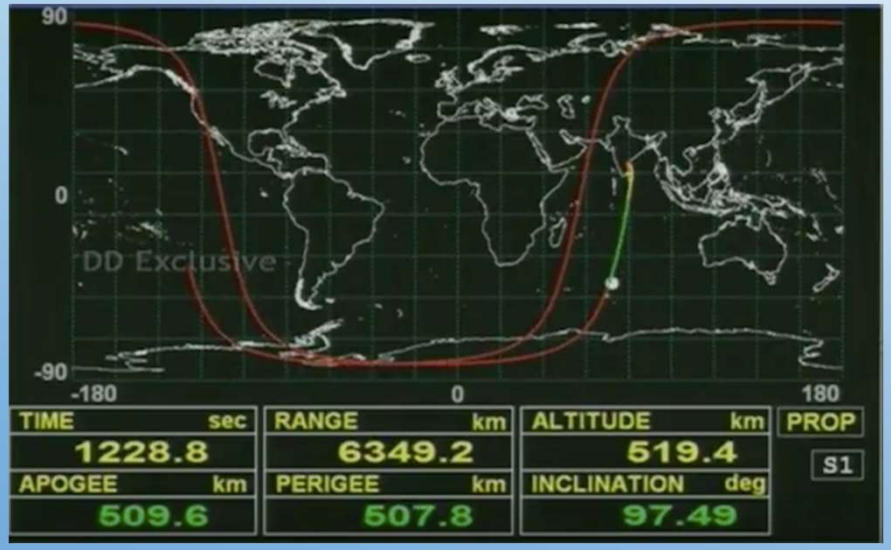
GIFTY BENJAMIN

VSSC

THIRUVANANTHAPURAM

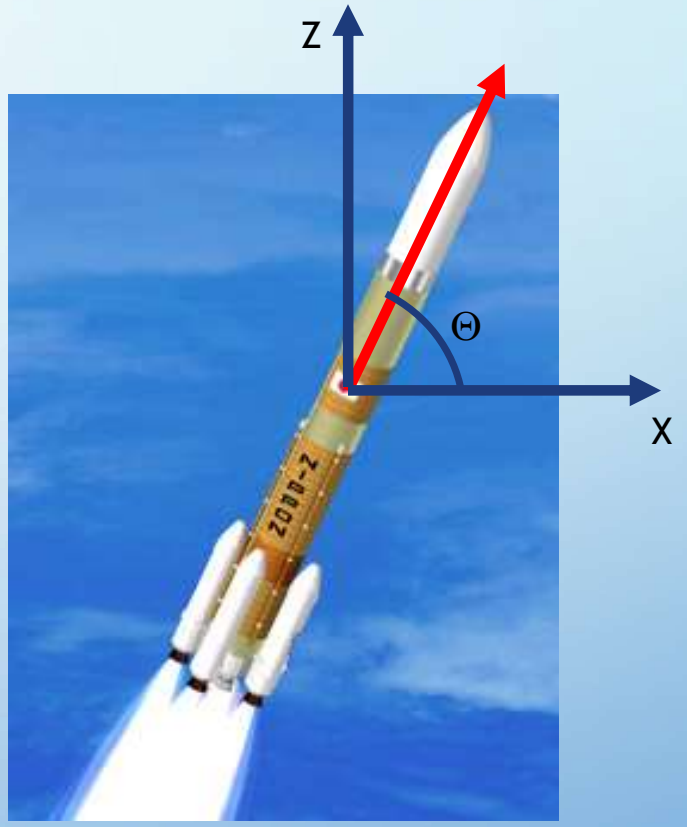
LAUNCH VEHICLES ?

- Designed to deliver payloads from earth to orbits in space
- Multistage vehicles using solid or liquid fuels
- Active variants >50

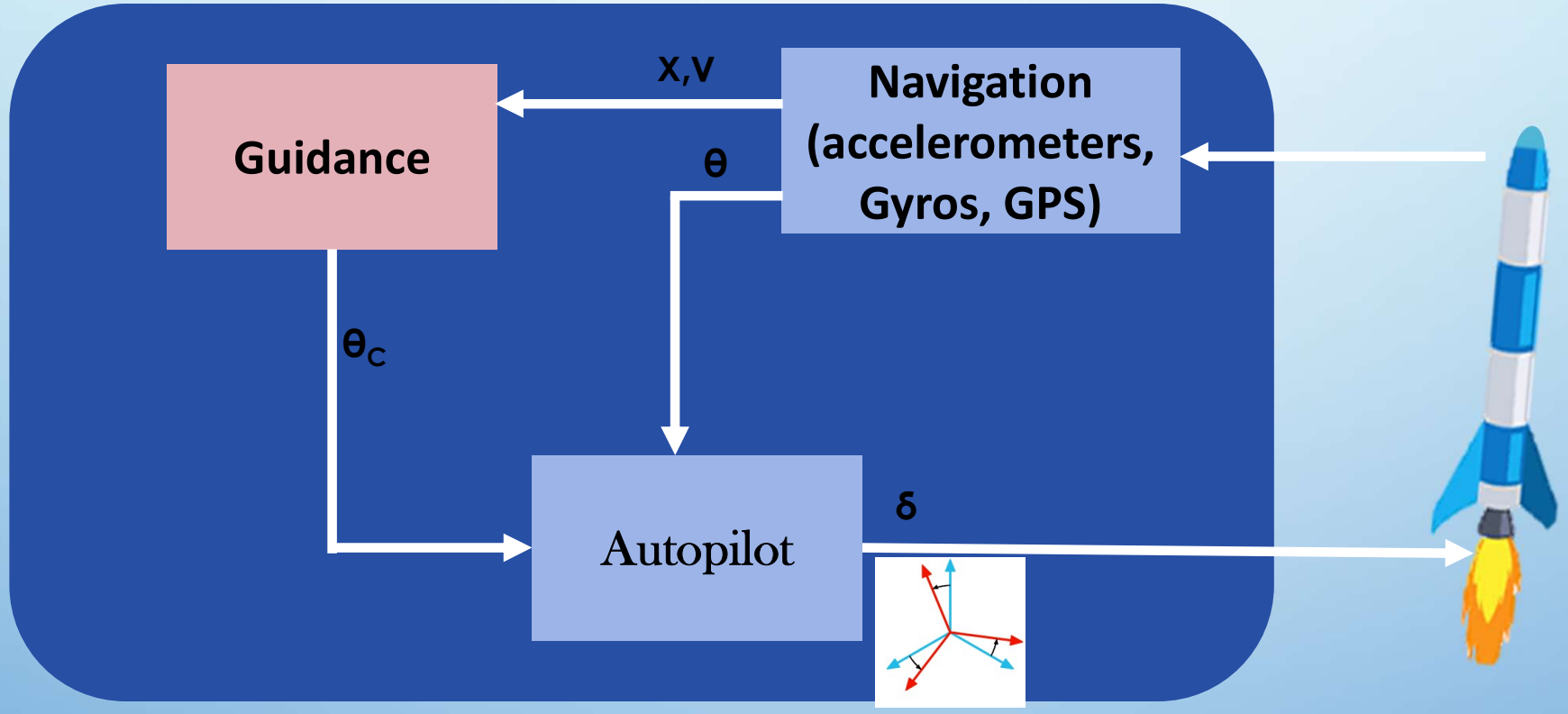


WHAT IS LAUNCH VEHICLE GUIDANCE ?

Guidance subsystem steers the launch vehicles along a optimal (desired) trajectory meeting mission requirements and satisfying constraints



MECHANISATION OF GUIDANCE



OPEN LOOP GUIDANCE VS CLOSED LOOP GUIDANCE

No	OPEN LOOP GUIDANCE	CLOSED LOOP GUIDANCE
1	Does not require any external measurements	Requires information of current vehicle states
2	Steering attitude stored as a look up table as function of time	Steering angle generated onboard
3	Computationally simple	Computationally complex
4	Sensitive to parameter variations	Robust to parameter variations
5	Meets targets approximately	Meets targets accurately

MEASURES OF PERFORMANCE OF GUIDANCE ALGORITHMS

1. SIMPLICITY :
Analytical,
Non iterative

2. EASY ONBOARD IMPLEMENTATION

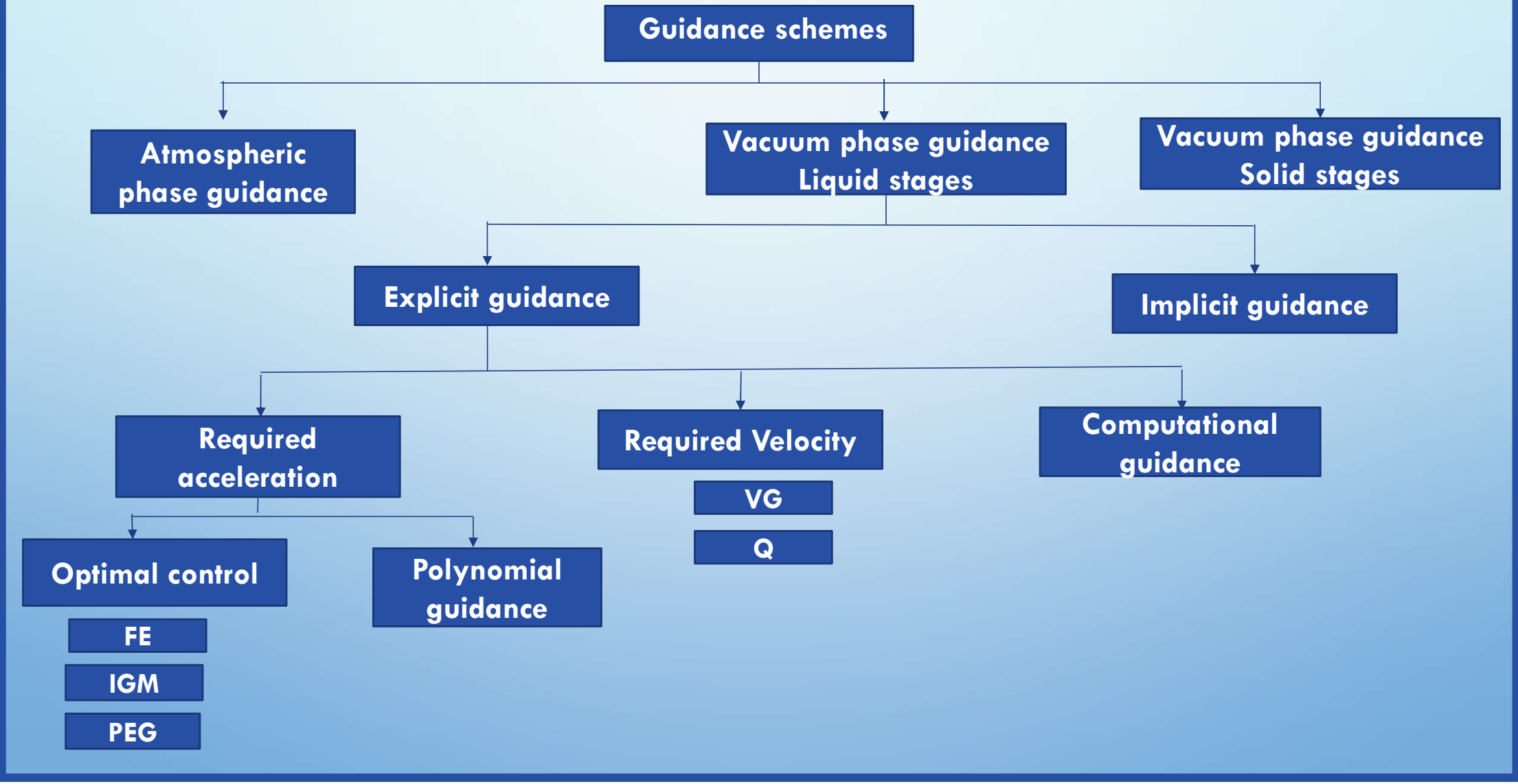
3. OPTIMALITY

4. ACCURACY

5. ROBUSTNESS

6. PRE-FLIGHT PREPARATIONS

GUIDANCE ALGORITHMS



OPTIMAL CONTROL BASED FORMULATION (UNIFORM GRAVITY)

Objective : Minimize t

State equations

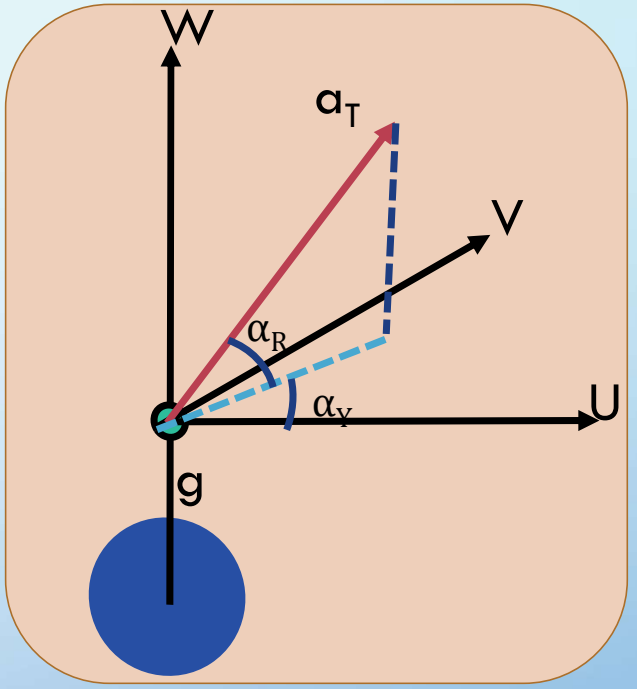
$$\dot{u} = a_T \cos\alpha_R \cos\alpha_y$$
$$\dot{v} = a_T \cos\alpha_R \sin\alpha_y$$
$$\dot{w} = a_T \sin\alpha_R - g$$
$$\dot{x} = u$$
$$\dot{y} = v$$
$$\dot{z} = w$$

Initial states:

$u_0, v_0, w_0, x_0, y_0, z_0$

Targets :

$u_f, v_f, w_f, x_f, y_f, z_f$



Co-state equations

$$\dot{\lambda_x} = \dot{\lambda_y} = \dot{\lambda_z} = 0$$
$$\dot{\lambda_u} = -\lambda_x$$
$$\dot{\lambda_v} = -\lambda_y$$
$$\dot{\lambda_w} = -\lambda_z$$

Initial co-states:

Not known

Final co-states:

Arbtitary

Optimal control law

$$\tan\alpha_R = \frac{\lambda_w}{\sqrt{\lambda_u^2 + \lambda_v^2}}$$

$$\tan\alpha_Y = \frac{\lambda_v}{\lambda_u}$$

LINEAR TANGENT STEERING LAW AND FLAT EARTH SCHEME

Assumptions

1. Flat earth (uniform gravity)
2. x_f is free $\Rightarrow \lambda_x = 0$

   λ_u = const ; $\lambda_v = \lambda_w = c_1 t + c_2$

Linear Tangent Steering

$\sec\alpha_Y \tan\alpha_R = At + B$

$\tan\alpha_Y = Ct + D$

Assumptions cont..

3. Small angle approx. for steering angles

Horizontal dynamics

$\dot{u} = a_T$ (thrust acceleration)

Vertical dynamics

$\dot{w} = a_T(At + B) - g$

$\dot{z} = w$

Out of plane dynamics

$\dot{v} = a_T(Ct + D)$

$\dot{y} = v$

Time to go computed by solving horizontal dynamics

Applications:

Ariane, PSLV, GSLV, LVM3

ITERATIVE GUIDANCE MODE

Small angle approximations does not hold good for large steering angles

Linear Tangent Steering modified

$$\tan\alpha_R = \tan\alpha_{RV} + (K_1 t + K_2)$$

α_{RV} = constant attitude required to achieve target velocity at predefined time

Parameters K_1 and K_2 are computed such that target distance is also met at the same time

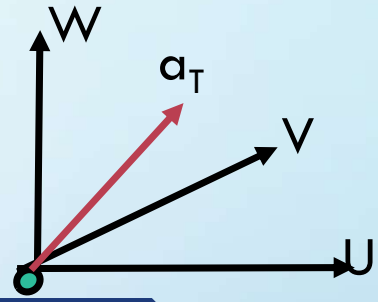
Time to go computed iteratively from Total required velocity

Application:
Saturn V

POWERED EXPILCIT GUIDANCE (PEG)

Linear Tangent Steering modified

$$\widehat{a_T} = \widehat{a_V} + \dot{a}_T(t-t_\lambda)$$



- Uses an iterative predictive corrector method for computing time to go
  - For velocity to be gained (Vgo), steering command is computed
    - Terminal velocity that can be achievable is predicted

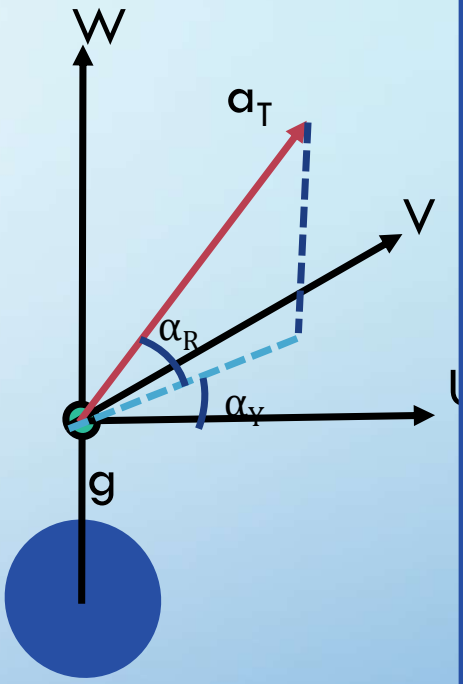
$$V_p = V + V_{grav} + V_{thrust}$$

- Vgo is updated as a function of $(V_d - V_p)$

Applications:
Space shuttle

POLYNOMIAL GUIDANCE

- Computes the total acceleration (thrust + gravity) required to meet the targets within a specified time
- Does not require propulsion model



Vertical dynamics

$\dot{w} = a_T sin\alpha_R - g$

Out of plane dynamics

$\dot{v} = a_T cos\alpha_R \, sin\alpha_y$

a_T =vehicle acceleration

Required acceleration in vertical

$w_r = \dot{z}_r = c_1 + c_2 tgo$

Required velocity and position

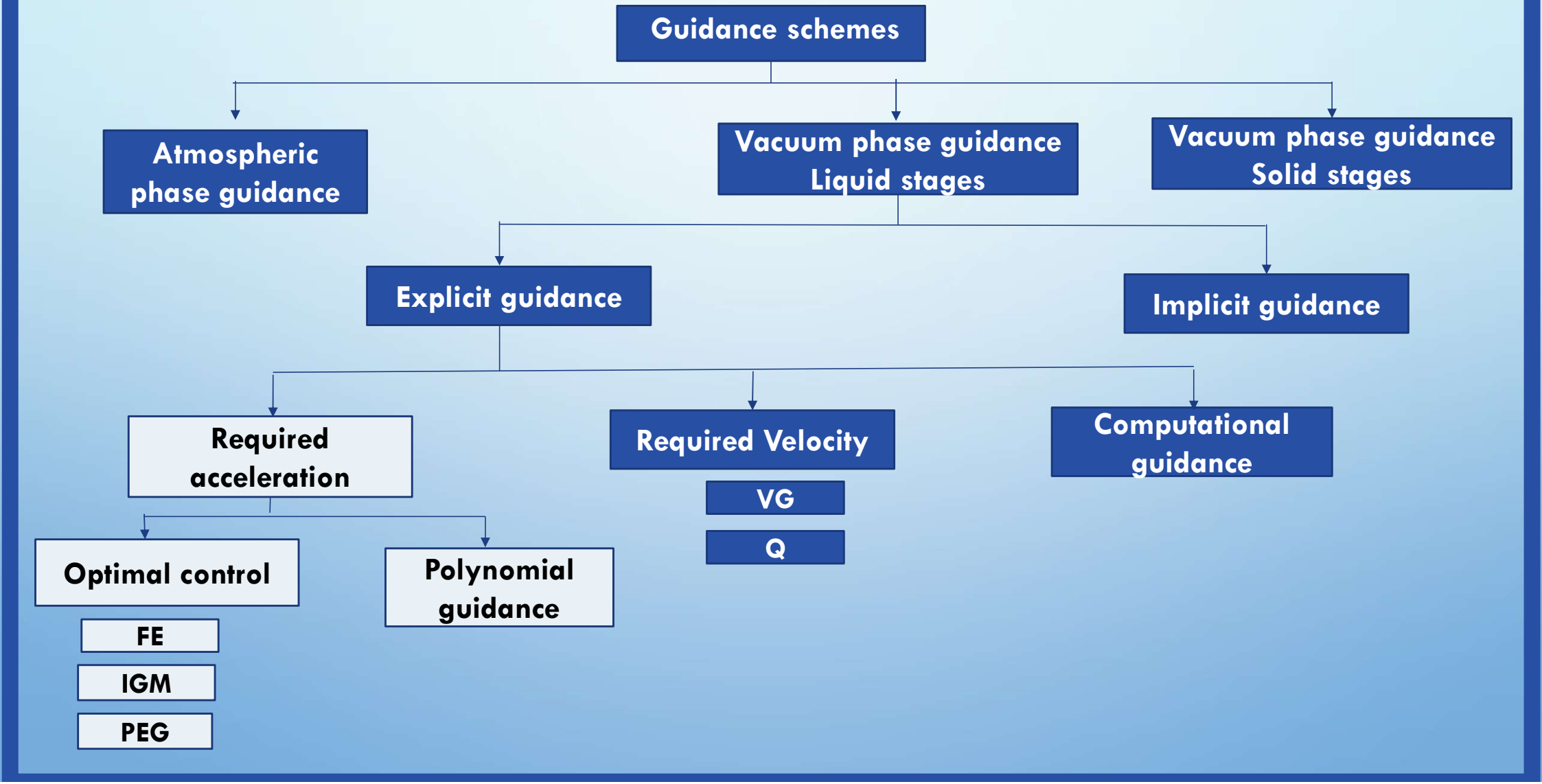
$\dot{z}_r = c_1 tgo + c_2 \, tgo^2 + \dot{z}_0$

$z_r = c_1 tgo + c_2 \, tgo^2 + \dot{z}_0 tgo + z_0$

Time to go computed iteratively by predictor corrector scheme

Applications:
PSLV

GUIDANCE ALGORITHMS



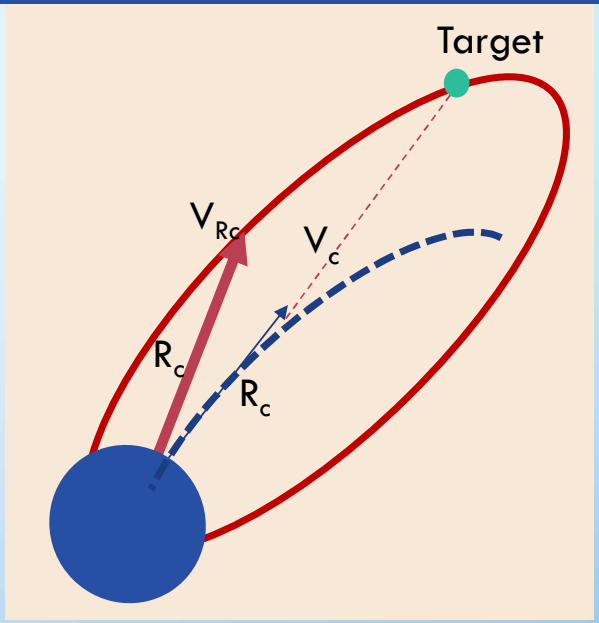
REQUIRED VELOCITY BASED SCHEMES

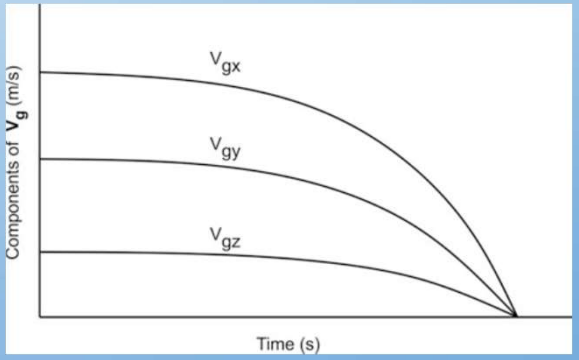
Required Velocity (V_r) is the velocity required at the current instant to achieve the target if thrust is terminated

Velocity to be gained

$$\overline{V_G} = \overline{V_R} - \overline{V_C}$$

Vehicle is steered such that all components of VG are brought to zero simultaneously

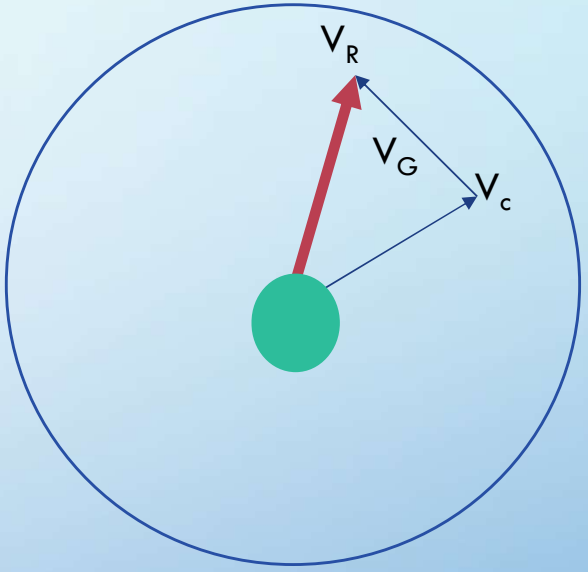




VELOCITY TO BE GAINED SCHEME

Cross product steering law

Steer the vehicle at a rate proportional to the cross product of thrust vector and VG vector



$$\omega = k(a_T \times VG)$$

Demerit

Not applicable for circular orbit injection

Applications:

PSLV (Intermediate stages)

Q GUIDANCE

Uses Cross product steering law to reduce velocity to be gained to zero.

According to Battin " All components of a vector shall be driven to zero by aligning the time rate of change of the vector to the vector itself"

$$\omega = k\left(VG \; X \frac{dVG}{dt}\right)$$

$$\frac{dVG}{dt} = -a_T - Q\,VG$$

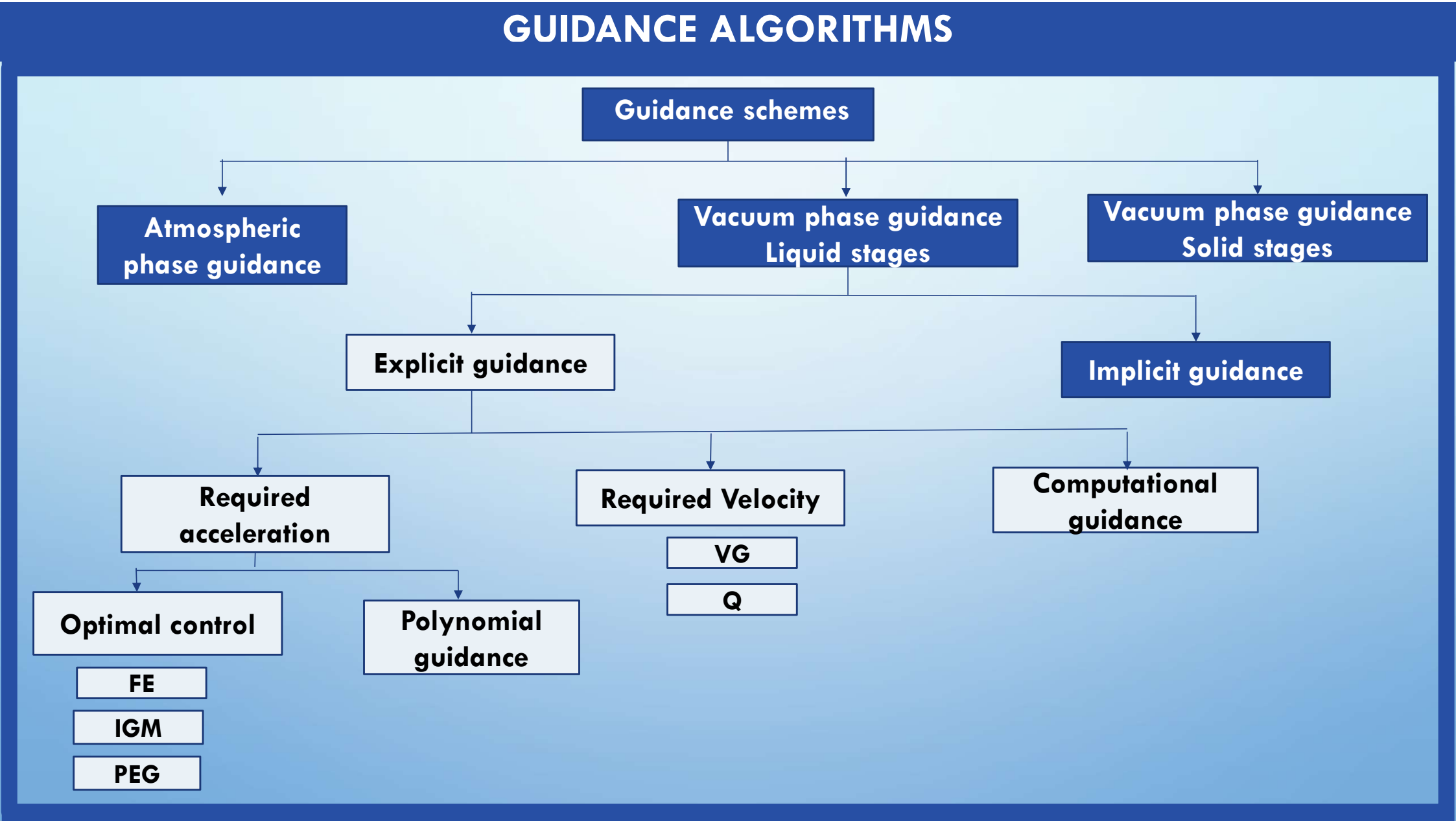
$$Q = \frac{\partial V_c}{\partial r}\Big|_{(r_f,\, t_f)}$$

Q is the sensitivity matrix

Demerit

Not applicable for circular orbit injection

GUIDANCE ALGORITHMS



IMPLICIT GUIDANCE

- Reference trajectory corresponding to a predefined performance is stored on board.
- Deviation of vehicle states from reference is used for steering modulation

Advantages

Simple and computationally efficient on-board

Drawbacks

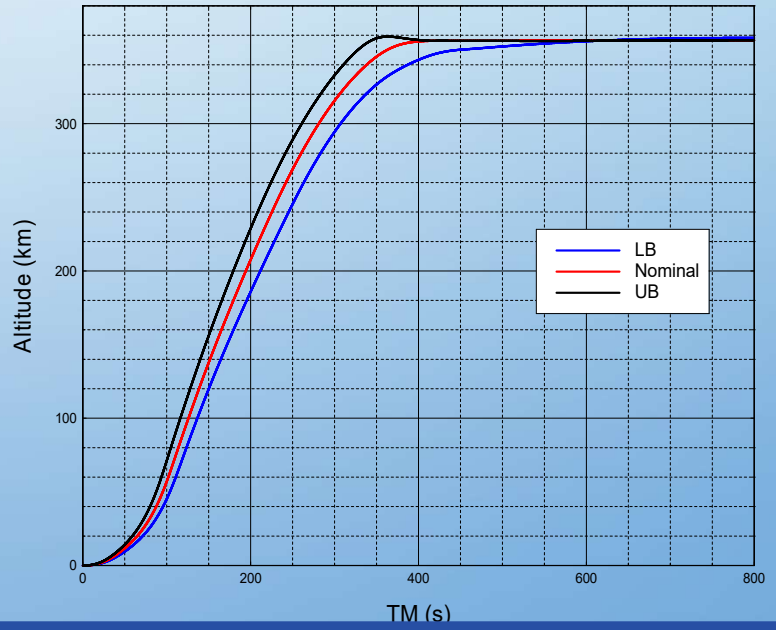
- Vehicle trajectory deviations are beyond predefined bounds, guidance performance deteriorates .
- Ground computations are more and depends on trajectory

GUIDANCE FOR SOILID STAGES

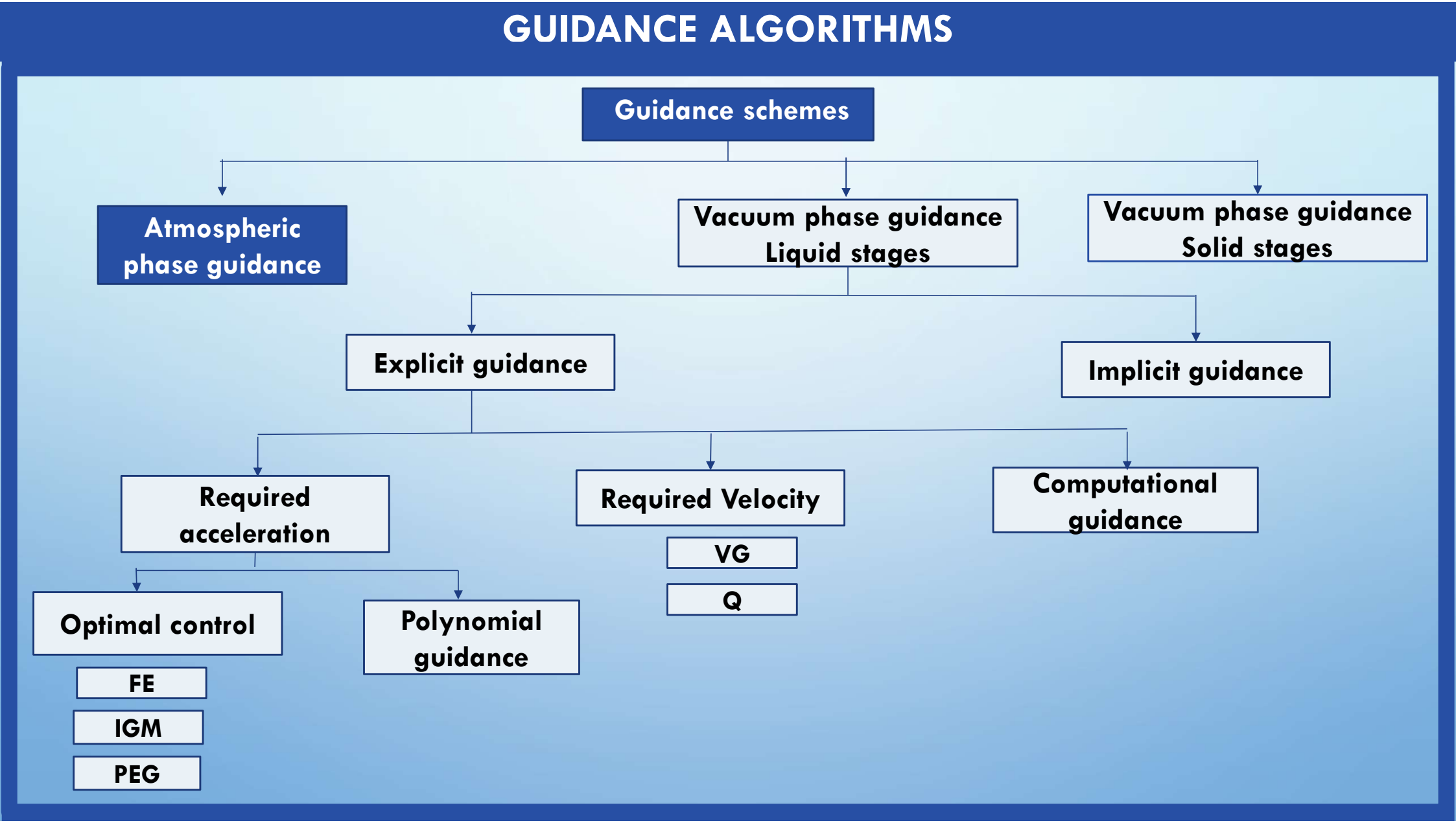
Challenges

- Solid stages have no provision for commanded thrust cut-off. Effective energy management strategies required for all stages.
- Velocity addition module is less capable with low thrust acceleration
- Hybrid solid stages can improve performance

- Energy management guidance which targets intermediate states based on current performance
- Targeting guidance for final stage

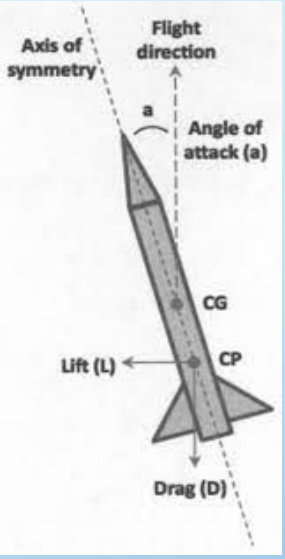


GUIDANCE ALGORITHMS



GUIDANCE FOR ATMOSPHERIC PHASE

- Aerodynamic forces are active which increases complexity of vehicle model
- Wind variations are expected. If angle of attack experienced by vehicle exceeds design value, aerodynamic loads exceeds design limit resulting in failure



- Conventional practice is to steer the vehicle with a steering look up table stored as a function of altitude (ISRO)/ relative velocity(STS)

- Closed loop guidance schemes steer the vehicle along the relative velocity vector.
- Information about vehicle angle of attack is obtained from lateral accelerometer To avoid large trajectory drift , CLG in targeting mode is executed after high Q regime

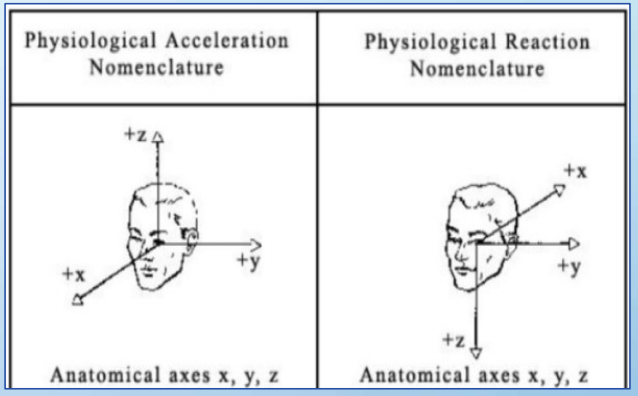
GUIDANCE FOR HUMAN RATED VEHICLES

MANRATING

Process of **designing, evaluating and assuring that the total system** can conduct the required human missions.

Constraints

Very High Acceleration levels induce g-levels on crew which should be within physiological limits



Mission /Guidance

Vehicle to be steered along an optimal trajectory meeting constraint on g-levels, heat
PEG provides throttle down command during first command.

ACTIVITY

Rate in a scale of 0 to5

Guidance scheme	Simplicity	Implementation	Optimality	Accuracy	Robustness	Ground computations
1						
2						
..						
10						

THANK YOU

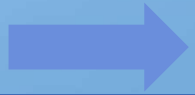
LAUNCH VEHICLE GUIDANCE AS OPTIMAL CONTROL PROBLEM

Mission objective is to deliver maximum payload into orbit

Maximizing payload means minimize fuel consumption

For liquid engines, constant thrust and mass flow rate is achievable, minimizing fuel consumption is minimizing burn time

For solid engines, thrust termination is infeasible which requires energy management strategies

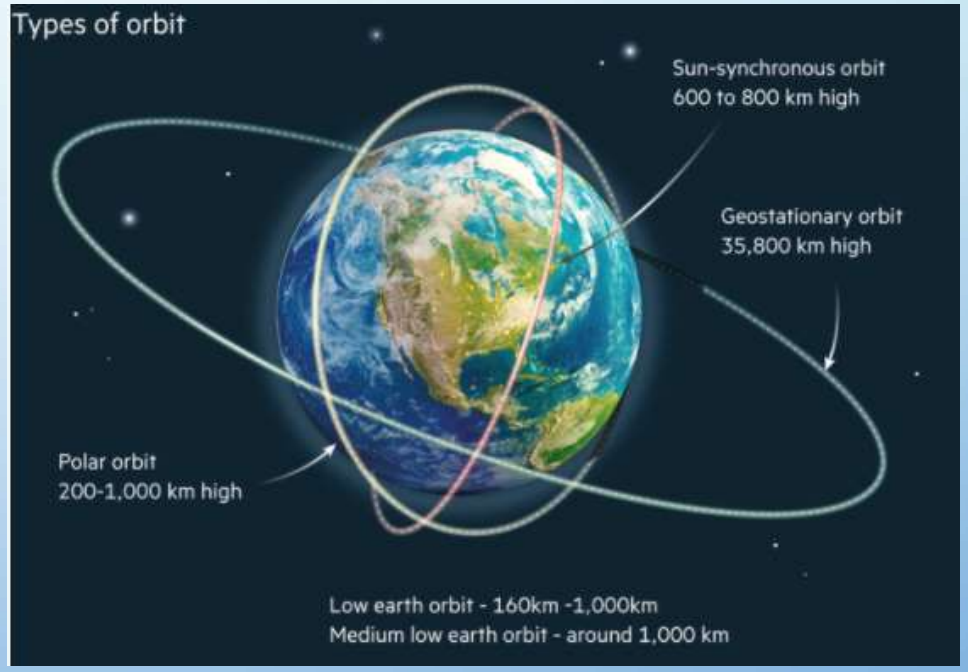


MISSION REQUIREMENTS

Deliver the payload in a specified orbit

- LEO orbits (350 to 1000km) (SSPO, Inclined orbits)
- Circular orbits

- Geosynchronous transfer orbits (36000km x 180 km)
- Interplanetary transfer orbit (Perigee 250km)
- Elliptical orbits (Inertially fixed)



ORBITAL ELEMENTS

Orbital size/shape

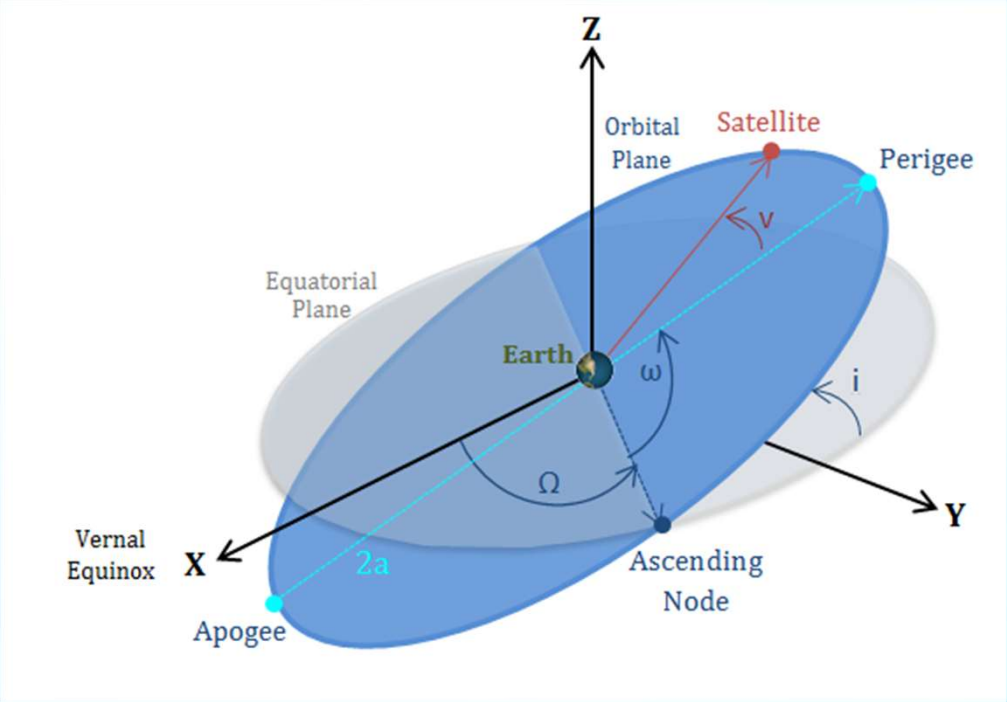
1. Semi major axis/2. Eccentricity
1. Apogee/ 2. Perigee

Orbital orientation in space

3. Inclination
4. Argument of perigee
5. Right Ascension /Longitude of Ascending node

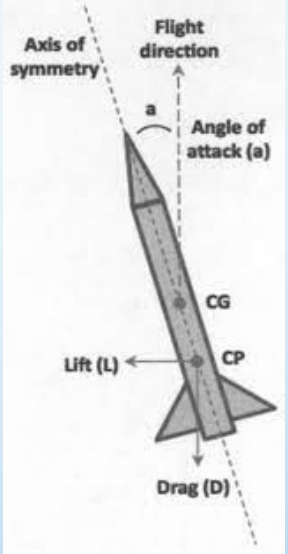
Satellite orientation

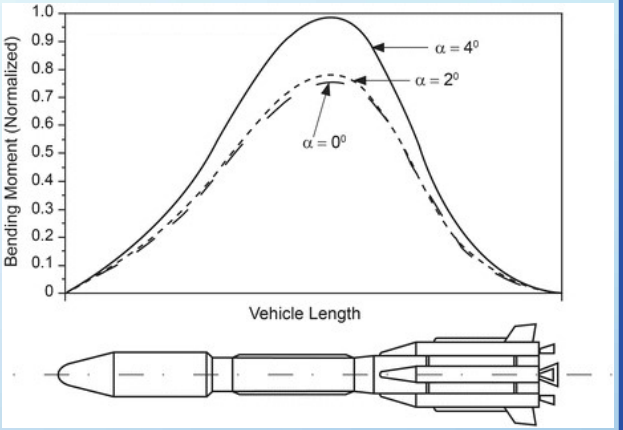
6. True Anomaly



MISSION CONSTRAINTS

Aerodynamic loads in atmospheric phase (< 80km)





Safe Impact of spent stages (Managed by proper thrust termination in liquid stages)

OPTIMAL CONTROL THEORY : BASICS

Problem definition

To find an admissible control u^* that causes the system

$$\mathbf{x(t)} = \mathbf{a(\dot{x}(t), u(t), t)}$$

to follow an admissible trajectory x^* that minimizes the performance measure

Performance measure

$$J(u) = h\left(x(t_f), t_f\right) + \int_{t_0}^{t_f} g(x(t), u(t), t)\, \mathbf{dt}$$

Hamiltonian

$$H(\mathrm{x(t)},\mathrm{u(t)},\mathrm{p(t)},\mathrm{t}) = \mathrm{g(x(t),\ u(t),t)} + p^T[a(x(t), u(t), t]$$

OPTIMAL CONTROL THEORY : BASICS

Necessary conditions

$$\dot{x}^*(\mathrm{t}) = \frac{\partial H}{\partial p}(x^*(\mathrm{t}), u^*(\mathrm{t}), p^*(\mathrm{t}),\mathrm{t})$$

$$\dot{p}^*(\mathrm{t}) = -\frac{\partial H}{\partial x}(x^*(\mathrm{t}), u^*(\mathrm{t}), p^*(\mathrm{t}),\mathrm{t})$$

$$0 = \frac{\partial H}{\partial u}(x^*(\mathrm{t}), u^*(\mathrm{t}), p^*(\mathrm{t}),\mathrm{t})$$

Boundary conditions

$$[\frac{\partial h}{\partial x}\, x^*(t_f), t_f) - p^*(t_f)]^T\, \partial x_f +$$

$$[H(x^*(t_f), u^*(t_f), p^*(t_f), t_f) + \frac{\partial h}{\partial t}\, x^*(t_f), t_f)]\, \partial t_f = 0$$